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ON THE CONCENTRATION OF DUST IN THE UPPER ATMOSPHERE LAYERS

by

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SUMMARY

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On the basis of photometric measurements of twilight sky brightness an estimate is made of dust concentration in the Earth's atmosphere and the values of concentrations and spatial density of the dust in the 40 to 135 km altitude range are obtained. The concentration of dust with height h varies according to the law $\sim h^{-7.2}$. Comparsion of the data obtained with the results of measurements on satellites has allowed to conclude that breaking up of particles of the near-terrestrial dust cloud or accumulation of fine particles by way of capture takes place at heights of 100 to 300 km above ground. The dust particles measured with the aid of satellites are not effective in the scattering of solar radiation in twilight conditions by comparison with finer particles.

* * *

The concentration of dust particles in the upper atmosphere layers may be investigated on the basis of the analysis of photometric observations of twilight sky brightness, provided we liberate ourselves from the influence of the secondary twilight conditioned by the scattering by the troposphere of light from the primary twilight ray.

* O KONTSETRATSII PYLI V VERKHNIKH SLOYAKH ZEMNOY ATMOSFERY.

The primary twilight brightness was determined in [1] by applying the method of [2], consisting in the observation of two points of solar vertical with a zenithal distance $Z = 70^{\circ}$. Measurements were conducted with an interference filter, centered on λ 0.57 micron, not transmitting any appreciable amount of twilight and night sky emission. The brightnesses of primary twilight so found were subdivided into a gaseous and dust components. It was found, that in the 40 — 70 km altitude range the brightness ratio of the dust to gas components is approximately constant and close to the unity. The same result was obtained independently in the work [3] for heights $h < 65$ km. According to [1], this ratio begins to rise noticeably at 80 km and at 130 km height the dust component is greater than the gas component by about 50 times.

The brightness of the twilight sky $\delta(h)$ as a function of the height h above the the terrestrial surface, can be approximately represented in the form

$$\delta(h) = c \int_{h}^{\infty} n(h)\, dh, \qquad (1)$$

where the constant c includes the intensity of the solar emission, the dust scattering factor and other parameters. The relative course of dust concentration $n(h)$ is determined with a precision to a constant multiplier

$$cn(h) = -\frac{d\delta}{dh} \qquad (2)$$

according ot brightness dependence $\delta(h)$ on h. We compiled in Table 1 the values of the brightness of the dust component $\delta(h)$, expressed in the number of stars 5 mg from sq.deg (2nd column, and the values of $cn(h) = -d\delta / dh$ (3rd column). The function $cn(h)$ represents the relative dust densities expressed in such units, that the formula (1) provides the density of the dust component of primary twilight in units of stars 5mg from sq. deg.

The dependence of $cn(h)$ on height h can be represented by a function of the form $\sim \exp(-h/H)$, where H is the height of the uniform dust atmosphere in the 40 — 130 km range, varying from 10 to 20 km. This dependence of cn (h) on h can be also advantageously approximated by a function of the form

$$cn(h) = 1.8 \cdot 10^{15} h^{-7.2}. \qquad (3)$$

TABLE 1

h, км	$\delta(h)$	$cn(h)$	$n(h)$ [$см^{-3}$]	h, км	$\delta(h)$	$cn(h)$	$n(h)$ [$см^{-3}$]
40	$4,4\cdot10^4$	$4,4\cdot10^3$	$1,3\cdot10^{-1}$	90	$2,1\cdot10^2$	$1,2\cdot10^1$	$3,6\cdot10^{-4}$
45	$2,2\cdot10^4$	$2,0\cdot10^3$	$6,0\cdot10^{-2}$	95	$1,5\cdot10^2$	8,6	$2,6\cdot10^{-4}$
50	$1,2\cdot10^4$	$1,2\cdot10^3$	$3,6\cdot10^{-2}$	100	$1,0\cdot10^2$	5,4	$1,6\cdot10^{-4}$
55	$6,5\cdot10^3$	$6,0\cdot10^2$	$1,8\cdot10^{-2}$	105	$7,8\cdot10^1$	4,4	$1,3\cdot10^{-4}$
60	$3,5\cdot10^3$	$3,0\cdot10^2$	$9,0\cdot10^{-3}$	110	$5,6\cdot10^1$	3,0	$9,0\cdot10^{-5}$
65	$2,0\cdot10^3$	$1,6\cdot10^2$	$4,8\cdot10^{-3}$	115	$4,1\cdot10^1$	2,2	$6,6\cdot10^{-5}$
70	$1,2\cdot10^3$	$1,0\cdot10^2$	$3,0\cdot10^{-3}$	120	$3,0\cdot10^1$	1,6	$4,8\cdot10^{-5}$
75	$7,4\cdot10^2$	$5,4\cdot10^1$	$1,6\cdot10^{-3}$	125	$2,2\cdot10^1$	1,2	$3,6\cdot10^{-5}$
80	$4,7\cdot10^2$	$3,2\cdot10^1$	$9,6\cdot10^{-4}$	130	$1,6\cdot10^1$	0,8	$2,4\cdot10^{-5}$
85	$3,1\cdot10^2$	$2,0\cdot10^1$	$6,0\cdot10^{-4}$	135	$1,2\cdot10^1$	0,54	$1,6\cdot10^{-5}$

As may be seen from the graph of Fig. 1, where the dependence cn (h) is plotted in the logarithmic scale, the points fit well the line with a -7.2 inclination. The constant $1.8 \cdot 10^{15}$ is chosen in such a way, that the integral (1) provide the observed brightnesses $\delta(h)$ of the dust component, expressed in the number of stars 5^m from sq.deg.

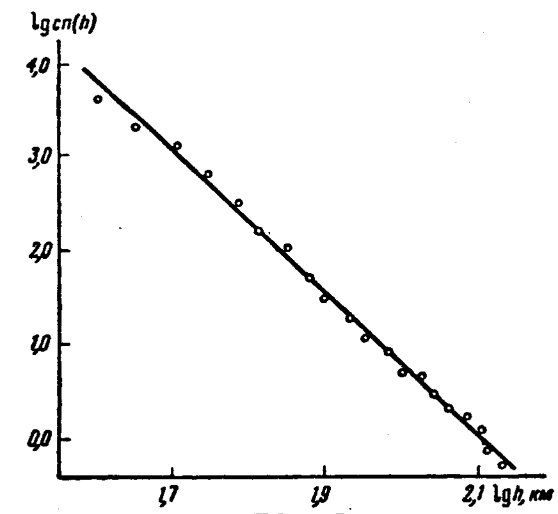

Fig. 1

The dependence cn (h) (Table 1) can be viewed as the dependence of dust concentration on the height h, expressed in relative units. In order to obtain the absolute values of dust concentration it is sufficient to determine the concentration at any given single height. Obtaining the absolute values of concentration from twilight observations is made difficult by the fact that the dimensions of dust particles, their albedo and the scattering indicatrix are not accurately known. However, the estimate of the absolute concentration can be made with some degree of precision. To that effect we shall utilize the altitude intervals of 40 – 60 km, where the intensity of light scattered by the dust is equal, as an average, to 0.9 of the intensity of the light scattered by atmosphere gases. Then

$$\sigma_d n(h) = 0{,}9\,\sigma_A n_A(h), \qquad (4)$$

where n (h) and n_A (h) are respectively the number of the dust particles and the number of molecules in 1 cm^3 at the height h; σ_A is the air scattering factor on 1 molecule; σ_d is the dust scattering factor on 1 dust particle, determining what part of the emission, incident on the dust particle, is scattered in a unitary solid angle at a scattering angle θ. Since σ_A and n_A (h) are known, n (h) can be determined if the factor σ_d is known. We may postulate $\sigma_d = q_{av} S_{av} f(\theta)$, where q_{av} is the mean value of the effectiveness factor of the considered particles, S_{av} is the average cross section area of these particles and f(θ) is the scattering function (indicatrix). Analogously, we have for the molecular diffusion $\sigma_A = \beta(3/16\pi)(1+\cos^2\theta)$, where β is the absorption coefficient for one molecule. Then, taking into account (4),

$$n(h) = 0{,}9[\beta n_A(h) / q_{cp} S_{cp} \alpha]$$
$$\left(\alpha = f(\theta) \Big/ \frac{3}{16\pi}\,(1+\cos^2\theta)\right). \qquad (5)$$

TABLE 2

Interval of radii, mc	S_{av}, cm^2
0,01—1	$2{,}0\cdot 10^{-10}$
0,01—10	$3{,}4\cdot 10^{-10}$
0,01—100	$3{,}5\cdot 10^{-10}$
0,05—1	$4{,}7\cdot 10^{-10}$
0,1 —1	$1{,}4\cdot 10^{-9}$
0,1 —10	$2{,}9\cdot 10^{-9}$
0,1 —100	$4{,}3\cdot 10^{-9}$

Direct collections of particles conducted at heights of 100 km [4], show that quite tiny particles, with radii to 0.01 mc, exist in the atmosphere. Correspondingly with the results obtained by direct measurements by means of rockets [4, 5], one may admit the following distribution for tiny dust particles

$$dn(a) = \frac{A}{a^3}\,da \ \text{ at } a > 0{,}05 \text{ мк}; \qquad dn(a)\,\frac{A}{0{,}05^3}\,da \ \text{ at } a < 0{,}05 \text{ мк}. \qquad (6)$$

Compiled in Table 2 are the average cross section areas for various intervals of particles' radii a_1 and a_2, computed for the admitted distribution (6), by the formula

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$$S_{cp} = \int_{a_1}^{a_2} \pi a^2 dn\ (a) \Big/ \int_{a_1}^{a_2} dn\ (a). \tag{7}$$

As may be seen from the Table, the average cross section area S_{av} varies little when the radius inteival of the considered particles widens toward the side of greater radii at invariable left boundary a_1 of the interval, so that the value of a_2 is immaterial in the determination of S_{av}. It is more important to know the left boundary of a_1. At decrease of a_1 from 0.1 to 0.01 mc, the value of S_{av} decreases by one order. However, at values $a < 0{,}1$ мк $(2\pi a / \lambda = 1)$ the effectiveness factor drops sharply [6] from values near two, to zero. That is why, for small values of a, the quantity $q_{av} S_{av}$ must be computed by formula

$$q_{cp} S_{cp} = \int_{a_1}^{a_2} q(a) \pi a^2 dn(a) \Big/ \int_{a_1}^{a_2} dn\ (a). \tag{8}$$

At the same time, a_1 is determined reliable as the greatest value of the radius, at which the subintegral function of the integral standing in the numerator of the expression (8) is practically zero. It was found that $a_1 = 0.03$ mc, i. e. that the particles with radius < 0.03 mc are not effective in the sense of light scattering (λ 570 mmc) in relation to coarser particles and can be excluded from consideration. It was obtained by way of numerical integration for particle dimension interval from 0.03 to 100 mk, that $q_{av} S_{av} = 1.3 \cdot 10^{-9}$ cm^2.

The absolute scattering indicatrix of dust particles can be taken in the form [7]

$$f(\theta) = \frac{1}{18{,}2} [1 + 11{,}1 (e^{-3\theta} - 0{,}009)]. \tag{9}$$

This indicatrix corresponds to atmosphere aerosols; it is obtained on the basis of a series of observations [8]. Inasmuch as our observations were conducted in the Sun's vertical at a point with a zenithal distance of 70°, to the considered twilight ray altitude interval from 40 to 60 km correspond scattering angles of 26 — 30°. At an indicatrix of the form (9) $\alpha = 2$ can be taken for the latter. Thus, assuming $q_{av} S_{av} = 1.3 \cdot 10^{-9}$ cm^2 and $\alpha = 2$, we obtain

$$n(h) = 1.4 \cdot 10^{-18} n_A(h), \tag{10}$$

where the value of the absorption factor β (λ 570 mmc) is taken equal to $4.1 \cdot 10^{-27}$. The last formula gives for the altitude interval 40 — 60 km the values of dust concentration compiled in Table 3 (column 3). The values of molecule concentrations are brought out in column 2 in accordance with the data of ref. [9].

TABLE 3

h, км	$n_A(h)$, см$^{-3}$	$n(h)$, см$^{-3}$	$k \cdot 10^{-5}$
40	$7{,}6 \cdot 10^{16}$	$1{,}1 \cdot 10^{-1}$	2,5
50	$2{,}4 \cdot 10^{16}$	$3{,}4 \cdot 10^{-2}$	2,8
60	$7{,}7 \cdot 10^{15}$	$1{,}1 \cdot 10^{-2}$	3,6

Having the values of dust concentration for the 40 — 135 km interval, expressed in relative units, (Table 1, col. 3) , and the values of concentration in the 40 — 60 km interval expressed in absolute units (Table 3, col. 3), it is possible to determine the coefficient k for the conversion of the indicated relative concentrations into absolute ones. The mean value of k, found equal to $3 \cdot 10^{-5}$, was utilized to obtain the absolute values of dust concentration in the 40 — 135 km altitude range, brought out in the 4th column of Table 1. They may be represented by the function

$$n(h) = 4.8 \cdot 10^{10}\, h^{-7.2}\ \text{cm}^{-3} \qquad (11)$$

The value of dust concentration $n(80) = 1 \cdot 10^{-3}$ at 80 km height, found by us, coincides with the value of concentration found by Mikirov [10] by measurements of sky brightness carried out with the aid of geophysical rockets, and is by two orders greater than the value $n(80) = 10^{-5}$, determined in [3] according to twilight observations. The concentration of dust, determined by us at 100 km, and which is $n(100) = 2 \cdot 10^{-4}$ cm^{-3}, exceeds by 6 to 7 orders that estimated by Moroz [11] by the results of direct measurements of dust particle flows conducted on rockets and satellites. Let us note first of all that in order to diminish by 6 to 7 orders the values of concentrations found by us, we must increase by the same number of orders the mean value of the effective area of particle cross section, admitted by us, the possibility of which is ruled out. The cause of such great a discrepancy, it seems to us, consists in that tiny particles, conditioning the scattering of solar light in twilight conditions, are not registered with the aid of satellites.

The concentrations found in [11], are based on the results of measurements, assuring the registration of particles with a mass exceeding 10^{-9} g, which corresponds to a particle of a 13 mk radius, if one estimates the density as equal to $0.1\ g\cdot cm^{-3}$. If we take as the starting point the law of particle distribution by sizes (6), admitted by us, and the value of concentration determined in [11], while $n(100) = 4\cdot 10^{-10} cm^{-3}$, we shall have

$$4\cdot 10^{-10} = \int_{13}^{\infty} \frac{A}{a_3}\, da.$$

This gives $A = 1.3\cdot 10^{-7}$. Then, the total number of particles with radii > 0.03 mk, will be equal to $5\cdot 10^{-5}$, which is only three times less than the value determined by us, which is $n(100) = 1.6\cdot 10^{-4}\ cm^{-3}$. Therefore, one may estimate, that the absolute concentrations determined by us according to photometric twilight observations, do not contradict the results obtained on satellites. However, substantially coarser particles are registered by way of direct calculations of the flow on rockets and satellites than those which are most effective in light scattering under twilight conditions. One may arrive at the same conclusion by comparing the relative course of cn (h), obtained by us, with the relative course of concentration obtained from measurements on satellites.

The direct measurements with the aid of rockets and satellites provide the flow of N particles. The concentration of particles $n(h)$ can be computed by the flow $N(h)$ according to formula $n(h) = 4N(h)/v$, provided the velocity v of particle flow relative to the rocket or the satellite is known. The following dependence of $N(h)$ on h has been obtained in [12]; here $N(h) = Bh^{-1.4}$ for heights > 100 km. If one estimates that v does not depend on h, the concentration $n(h)$ will be proportional to $N(h)$, and in this way, $n(h) \sim h^{-1.4}$. Our twilight determinations of concentration give $n(h) \sim h^{-7.2}$.

Therefore, there exists in the region 100 — 135 km, where measurements were conducted by the two methods considered, an essential discrepancy between the character of the dependence n (h), obtained by twilight measurements of brightness and by measurements of particle flow with the help of satellites. In order to verify whether or not the relative course of dust concentration at heights > 135 km is determined by the dependence $n(h) \sim h^{-1.4}$, we must assume $h_1 = 135$ in the expression of the integral

$$\delta(h_1) = \int_{h_1}^{\infty} B h^{-1.4}\, dh \qquad (12)$$

and determine the constant B in such a way, that the integral gives the brightness of the dust component of the twilight sky for the height of the twilight ray at 135 km, i.e. — that our dependence of the form $cn(h) \sim h^{-7.2}$ (Table 1, col. 3) continues uninterruptedly by a dependence of the form $n(h) \sim h^{-1.4}$. Then, $B = 5.2 \cdot 10^2$ and the brightness $\delta(135) = 3 \cdot 10^2$ stars 5 mg from sq.deg, which exceeds by one order the corresponding brightness $1.2 \cdot 10^1$ obtained by our observations. Consequently, the relative course of the form $n(h) \sim h^{-1.4}$ is found to be too slanting. Therefore, we shall admit, that the dependence is determined by the same function as at $h < 135$ km, i.e. $n(h) \sim h^{-7.2}$ up to a certain height h_1, and at $h > h_1$ — by the dependence $n(h) \sim h^{-1.4}$. This value h_1 is determined from the condition that the brightness $\delta(h_1)$ be, according to (12), acceptable from the viewpoint of photometric observations. It is established by way of probes, that the least value of h_1, satisfying this requirement, may be taken equal to 300 km, with $B = 2.6 \cdot 10^{-3}$. At the same time, the brightness $\delta(300)$ is found to be equal to 1.9 stars 5 mg from sq.degree. Taking into account the values of the brightness of the night sky, such brightness of the dust component may be admitted as the upper threshold value.

Therefore, it stems from the photometric measurements, that the obtained dependence of particle concentration n (h) [12] cannot represent the concentration of particles responsible for the scattering of solar radiation at heights greater than 300 km. Consequently, the divergences in the laws of variation of dust particle concentration from the distance h, obtained by photometric observations and by measurements on rockets and satellites, surely takes place in the 100 — 300 km region. At the same time, the possibility is not excluded that these divergences are observed also above 300 km. If one estimates, that they are conditioned by the variation of the velocity v of particle encounter with the cosmic missile as a function of height, the dependence of the velocity on height will have the form $v(h) = h^{-5.8}$. According to this dependence the velocity must increase from 100 to 300 km approximately by 600 times, which is unrealistic, inasmuch as as at 100 km even the particles, fixed relative to Earth, will be endowed with a high velocity relative to the cosmic missile. That is why the velocity variation should be rejected as a cause of discrepancy.

It must then be assumed that the discrepancy considered in the 100 — 300 km region is conditioned by the presence in that region of fine dust, not registered with the help of satellites, but still scattering the solar radiation; this stemmed already from the comparison of absolute concentrations at the height of 100 km. But the fact that the concentration of fine dust, responsible for the twilight scattering of solar radiation, drops with the increase of h substantially faster that the concentration of coarser particles registered on satellites, may be considered as proof that the altitude region from 100 to at least 300 km is the place of formation of tiny dust particles (or place of accumulation). Therefore, the analysis conducted provides the basis to assume that an intensive breaking up of particles in the near-terrestrial dust cloud takes place, or an accumulation of tiny particles because of capture. The height of 300 km is not established precisely and is rather derived starting from the requirement that the dependence $n(h) \sim h^{-1.4}$, does not contradict the photometric measurements. It is quite probable that this region extends beyond 300 km.

The analysis conducted by us shows, that the dust particles of the near-terrestrial dust cloud, currently being detected by satellites, are little effective in the sense of scattering the solar radiation by comparison with tinier particles, conditioning the dust component of the night airglow. At the same time, the possibility is not excluded of the presence in the Earth's environment of tiny particles which contribute to the brightness of the zodiacal light, but are not registered with the aid of satellites. In connection with this, it would be very interesting to obtain samples of matter, taken in the vicinity of the Earth with the help of satellites reentering the Earth.

*** THE END ***

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